Forward Modeling of Stratigraphic Sequences at Continental Margins

Michael S. Steckler
Lamont-Doherty Earth Observatory of Columbia University
Palisades, NY 10964-8000
phone: (914) 365-8479 fax: (914) 365-8179 e-mail: steckler@ldeo.columbia.edu

Grant Number N00014-95-1-0076

LONG TERM GOALS

The goal of the Stratigraphy project of the STRATAFORM program is *to understand the creation of the preserved stratigraphic record on continental shelves and slopes as the product of physical processes acting with spatial and temporal heterogeneities.* I am using numerical models to provide insight into the formation and preservation of stratigraphic sequences at margins. My goal is to obtain a quantitative understanding of the interactions of environmental parameters and their influence on stratal architecture and facies distribution. I wish to be able to decipher the stratigraphy on margins to read the geologic record of the past and predict future stratigraphy.

OBJECTIVES

I wish to understand how sea level and other factors control the formation of the stratigraphic record at margins. The stratigraphy at margins is packaged into unconformity-bound sequences whose form and lithology record the active processes at the margin. The influences of individual processes that create these sequences are only partly understood. My aim is to quantitatively determine the system response of margins to different forcing functions sufficiently to be able to both predict stratigraphy and invert observed sequence architecture for geologic history.

APPROACH

I am using numerical models as a tool to provide insight into the formation and preservation of stratigraphic sequences at continental margins. In conjunction with others, I have constructed, and am continuing to improve, an interactive computer model of stratigraphic sequences at continental margins, and am applying these models to the STRATAFORM field areas. The work is proceeding along three lines:

(1) Development of 2-D models focused on combining parameterizations of the dynamic sedimentologic and morphologic processes that control sediment deposition and erosion within a framework that accounts for geologic processes that effect accommodation .

(2) Numerical experimentation with the model to determine the stratigraphic consequences of the processes and parameter interactions. Examination of margin data to calibrate the model. Application of the model to the sequences in the field areas.

(3) Analysis of the geologic record sedimentary and geomorphologic processes in New Jersey and California. A particular focus is backstripping to reconstruct the margin development. The modeling of the two margins provides constraints for unraveling the control of sequence development.

In this work I am collaborating with Greg Mountain (L-DEO) on the interpretation and modeling of the New Jersey margin. I have been collaborating with Don Swift (Old Dominion University), John Carey (Texas Pan-American College) and Chris Reed and Alan Niedoroda (Woodward-Clyde) in incorporating shelf sediment transport models and facies models into the stratigraphic model, and applying the model to the Eel River basin. I am working with a larger group of STRATAFORM modelers and colleagues to incorporate and improve sediment transport models from the coastal plain to the continental rise. I am working with James Syvitski to coordinate our modeling efforts. I am coordinating with my co-chair, Jamie Austin (UTIG) to manage the stratigraphy project efforts.

WORK COMPLETED

The interactive stratigraphic modeling software, SEQUENCE, continues to be updated. We have replaced the geometric module for coastal plain sedimentation by one that uses a diffusion-based algorithm. The coastal plain is based on the Paola et al (1992) diffusion model. The shelf transport is based on the Niedoroda et al. (1995) behavioristic model. This has enabled improved estimation of shoreline positions during model runs, particularly the response to changes in sediment supply. We have performed sensitivity experiments to investigate the response of this new model and applied it to a data set from the Ganges-Brahmaputra delta (Goodbred et al., submitted).

Plans for completing the development of the 2D version of SEQUENCE were laid this year. We will incorporate and calibrate modules for four distinct transport/depositional regimes with moving boundaries. The modules will contain provision for multiple grain sizes and a subgrid-scale algorithm for fine-scale facies.

Sequential backstripping and reconstruction of the paleobathymetry and geometry of the New Jersey margin from the coastal plain to the mid-shelf has been completed (Steckler et al., 1999). This work has now been extended to the upper continental slope. This enabled reconstruction of the New Jersey margin from the Oligocene to the present.

Landmark seismic interpretration software has been installed in the multichannel seismic processing center and New Jersey seismic data have been loaded onto it. The seismic interpretations are being transferred to this system, which will enable completion of the mapping of sequence geometries and examination of along-strike variability.

RESULTS

The backstripping of the NJ margin has yielded an improved geologic history of the margin. Enhanced terrigenous sediment supply starting in the Oligocene caused progradation of clinoforms over the preexisting carbonate ramp margin. The clinoform rollovers represent a new shallower shelf edge that advanced across the margin. Analysis of the sediment volumes in the sequences revealed significant fluctuations in the sediment supply through time (Fig. 1). Two major peaks reveal order of magnitude increases in the sediment supply. These peaks correlate with major climatic shifts as indicated by $\delta^{18}O$. A middle Miocene peak corresponds to the onset of permanent Antarctic glaciation, and a Pleistocene peak corresponds to the start of the large Northern Hemisphere glacial cycles. Seismic records reveals that half of the NJ margin progradation occurred in the middle Miocene between 16.6 and 13.1 Ma. The contrast in progradation rate is made clear by the observation that the amount of Late Miocene to Pliocene progradation (11.5-1.8 Ma) is equaled by the Pleistocene progradation (<1.8 Ma). These order of magnitude increases in sediment supply allowed the preservation of higher frequency eustatic cycles at the times of peak sediment supply. Similar pulses at other margins indicate that this may be a global phenomenon.

The results show that the sedimentation peaks slightly postdate the $\delta^{18}O$ shifts. I interpret this to indicate that the sediment pulses represent transient readjustments of the continental landscape to climatic shifts. The climatic shifts altered the form of the equilibrium landscape; the earth response was erosion to reestablish a landscape adjusted to the climate. The timing of the peak and its decay suggest about a million year time scale for this readjustment process. Thus landscape readjustment times appear to greatly exceed the periods of current glacial climatic and sea level cycles. A paper discussing these results is in preparation.

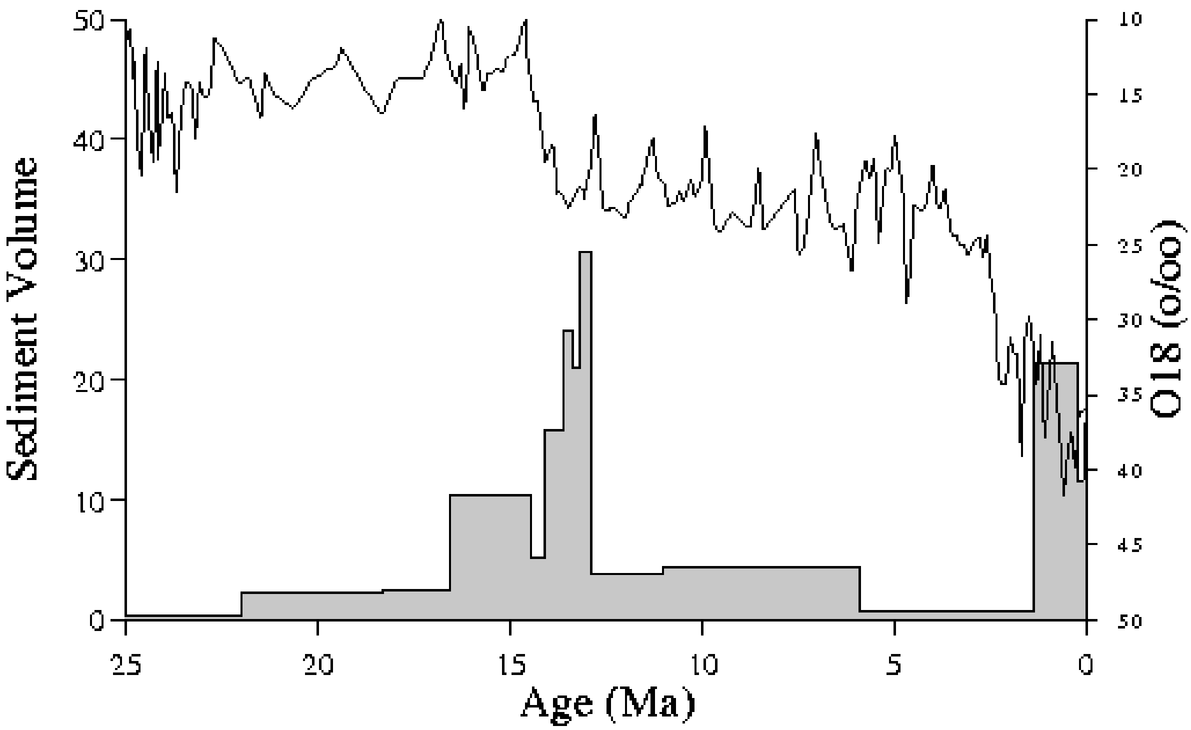

Figure 1. Superimposed plots of the sediment flux through time measured on the New Jersey margin and the global □^{18}O curve, a proxy for ice volume and temperature change. The large peaks in sediment o the New Jersey margin occur immediately following the largest climatic event as indicated by the □^{18}O curve.

The SEQUENCE modeling code underwent significant revision and further upgrades are planned. Sediment transport in SEQUENCE has had two options. A geometric model has been used for long-term modeling primarily for the New Jersey margin (Steckler et al., 1998, 1999, 2000). This version has been very successful at capturing the major features of the sequences imaged on the New Jersey margin. I found that differences in preexisting topography and sea level amplitude can explain the contrasting sequence architectures of the Early Miocene and Plio-Pleistocene sequences in New Jersey. A paper about these results is in preparation.

However, the geometric model is limited because depositional slopes have to be prescribed. A hybrid geometric-behavioristic model (Carey et al., 1999, in prep.) has been used for shorter-term modeling, primarily for the Eel River margin. It combines geometric components with a numerical simulation of shelf sediment transport. This version displays dynamic effects on shelf evolution that the geometric model cannot simulate. This is important for explaining preservation patterns on the Eel River margin. However, the hybrid model is showing the limitations of combining these two disjoint schemes.

Neither version of SEQUENCE can adequately predict shoreline movement due to fluctuations in sediment supply. Aside from feedbacks in the model, the dependence of the shoreline on relative sea level and sediment supply has to be prescribed. This has been corrected this year by the changeover to a fully dynamic transport model. Figure 2 shows an example run of shoreline progradation from a test run.

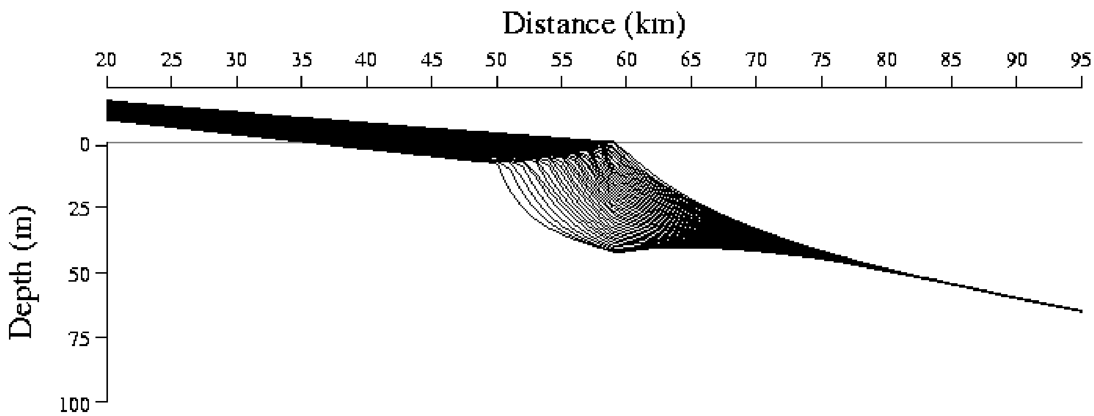

Figure 2. Model run showing shoreline progradation due to sediment influx with no changes in sea level. Timelines are 500 y apart. The preserved sediments are deformed by the influence of compaction and isostasy.

This new version of SEQUENCE has been tested using a data set from the Ganges-Brahmaputra Delta. Sediment records show that there was an major increase in sediment supply to the delta during the early Holocene related to the onset of the SW monsoon. As a result, this delta differs from most other around the world in that it started prograding at ~11 Ka, during the rapid global sea level rise, rather than at ~6 Ka at the end of the sea level rise. I have used the latest version of SEQUENCE to model the trangression and regression of the Ganges-Brahmaputra Delta over the last 30 Ka. The modeling showed that this transient increase in sediment supply was enough to halt the transgression and start progradation of the delta (Fig. 3) (Goodbred et al., submitted). The previous version of SEQUENCE could not model this phenomenon.

IMPACT/APPLICATIONS

The changes in continental margin morphology and sediment supply seen at New Jersey appear to be widespread and apply to other margins. They are hypothesized as being related to the climatic changes of the Cenozoic. I conclude that widespread changes in morphology and sediment supply at margins during the Tertiary are related to global climate. The peaks in sediment supply at climatic transitions highlights the importance of transients in the landscape and stratigraphic response to external forcing. These findings will enable better prediction of the stratigraphy at other margins.

The new version of SEQUENCE is able to realistically deal with changes in sediment supply during model runs. Such changes are expected to occur during sea level cycles, although data on the relationship of sea level and sediment supply are limited. The response of the shoreline to changing conditions (e.g., sea level, tectonics, sediment supply) no longer is proscribed, but determined by the coupling between the transport processes for the land and the sea. This holds great promise for more accurate prediction of the long-term morphodynamic response of margins to environmental change and more accurate predictions of stratigraphy.

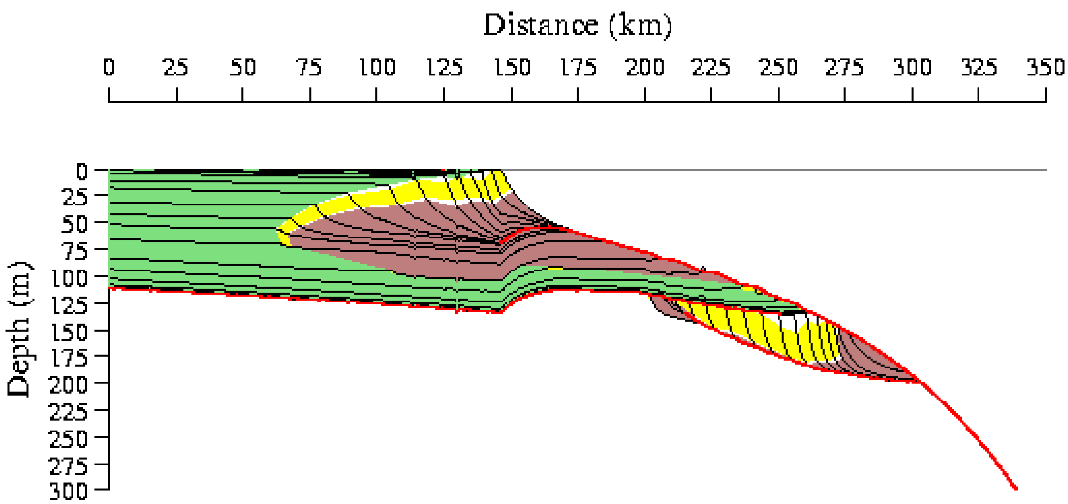

Figure 3. Simulation of the late Pleistocene to present stratigraphy of the Ganges-Brahmaputra Delta. Timelines are drawn every 1000 y. The model shows the deposition of a lowstand delta followed by a transgression that is halted at ~11 Ky by a transient increased sediment flux. In runs without the increased flux, the transgression continues until ~6 Ky. Green: non-marine, yellow: shoreface, and maroon: marine deposits. Red lines are erosional unconformities.

TRANSITIONS

Software is being used at several other universities for both STRATAFORM and other sequence stratigraphic investigations. I will be distributing software more widely, such as to INFREMER to model the Gulf of Lion. I will be using the software to model Jurassic Tank results.

RELATED PROJECTS

Reconstructions of West African margins using the sequential backstripping (Lavier et al., subm.) show strong similarities with the NJ margin. In particular, peaks in sediment supply occur at the same times. Other margins around the world show similar prograding sequence architectures. I conclude that widespread changes in morphology and sediment supply at continental margins occurred during the Tertiary and they are related to global climatic change.

I used the latest version of SEQUENCE to model the stratigraphy of the Ganges-Brahmaputra Delta. This largest delta in the world differs from most others because large temporal changes in sediment supply halted the Holocene transgression during the rapid sea level rise and started progradation of the delta (Goodbred et al., submitted).

REFERENCES

Carey, J.S., D.J.P. Swift, M.S. Steckler, C. Reed and A. Niedoroda, 1999. High resolution sequence stratigraphic modeling: 2. The influence of sedimentation processes, in J. Harbaugh, L. Watney, G. Rankey, R. Slingerland, R. Goldstein and E. Franseen (eds.) Numerical Experiments in Stratigraphy, SEPM Memoir 62, 151-164.

Goodbred, Jr, S.L., S.A. Kuehl and M.S. Steckler, Character of the Ganges-Brahmaputra delta sequence: Example from a tectonically-active, high-yield margin, Sedimentary Geology, submitted, 2000.

Lavier, L., M.S. Steckler and F. Brigaud, submitted. Climatic and tectonic controls on the Cenozoic evolution of the West African continental margin, Marine Geology.

Niedoroda, A.W., C.W. Reed and D.J.P. Swift A. Arato and K. Hoyanagi, 1995. Modeling shore-normal large-scale coastal evolution, *Marine Geology, 126*, 180-200.

Paola, C., P. L. Heller, and C. L. Angevine, 1992. The large-scale dynamics of grain-size variation in alluvial basins, 1: Theory, *Basin Res., 4*, 73-90.

Steckler, M.S., G.S. Mountain, N. Chrisitie-Blick, K.G., Miller, 1998. Controls of the architecture of prograding sequences on the New Jersey continental margin: Results from numerical modeling, EOS, 79, F468.

Steckler, M.S., G.S. Mountain, K.G. Miller and N. Christie-Blick, 1999. Reconstruction of Tertiary progadation and clinoform development on the New Jersey passive margin by 2-D backstripping, Marine Geology, 154, 399-420.

Steckler, M.S., 2000. Reconstruction of the Cenozoic Stratigraphy at the New Jersey Margins: The Interaction of Climate, Sediment Supply and Sea level, Geological Society of America, Northeast Section Annual Meeting, Abstracts with Program, 32, A-76.

PUBLICATIONS

Carey, J.S., D.J.P. Swift, M.S. Steckler, C. Reed and A. Niedoroda, 1999. High resolution sequence stratigraphic modeling: 2. The influence of sedimentation processes, in J. Harbaugh, L. Watney, G. Rankey, R. Slingerland, R. Goldstein and E. Franseen (eds.) Numerical Experiments in Stratigraphy, SEPM Memoir 62, 1999, 151-164.

Goodbred, Jr, S.L., S.A. Kuehl and M.S. Steckler, Character of the Ganges-Brahmaputra delta sequence: Example from a tectonically-active, high-yield margin, Sedimentary Geology, submitted, 2000.

Steckler, M.S., G.S. Mountain, K.G. Miller and N. Christie-Blick, 1999. Reconstruction of Tertiary clinoform progadation on the New Jersey passive margin by 2-D backstripping, Marine Geology, 154, 399-420.

Steckler, M.S., C.W. Reed, D.J.P. Swift, and A.W. Niederoda, 1999. High resolution sequence stratigraphic modeling: 1. The interplay of sedimentation, erosion and subsidence, in J. Harbaugh, L. Watney, G. Rankey, R. Slingerland, R. Goldstein and E. Franseen (eds.) Numerical Experiments in Stratigraphy, SEPM Memoir 62, 139-149.

Steckler, M.S., 2000. Reconstruction of the Cenozoic Stratigraphy at the New Jersey Margins: The Interaction of Climate, Sediment Supply and Sea level, Geological Society of America, Northeast Section Annual Meeting, Abstracts with Program, 32, A-76.